The variation changes of the precipitation – runoff relationship

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Abstract: The variation of the rainfall-runoff relationship t will lead to the disappearance of the consistency assumption of engineering hydrology, which will influence the planning, design, operation management and development and utilization of water resources. Therefore, the variation diagnosis of the rainfall -runoff relationship has become one of the hot topics and key issues in this area. In this study, the variation points of the precipitation-runoff relationship are defined, the difference between the variation point and the mutation point is distinguished, and the method of variation classification is proposed based on the the dimensionless mean and variation coefficients. Then, a comprehensive diagnosis system of the rainfall-runoff relationship variation is constructed on the basis of systematically summarying and analyzing of the diagnosis method of rainfall - runoff relationship variation at home and abroad. Taking the Weihe River Basin as a case study, the comprehensive diagnosis system is verified by applying it to test the change point the annual runoff time series at the Huaxian hydrological station. And the results show that the comprehensive diagnosis method proposed in this paper is scientific and reasonable.

Hydrological elements; Vatiation changes; Comprehensive detecting system; Weihe River basinAbstract: The variation of the rainfall-runoff relationship t will lead to the disappearance of the consistency assumption of engineering hydrology, which will influence the planning, design, operation management and development and utilization of water resources. Therefore, the variation diagnosis of the rainfall -runoff relationship has become one of the hot topics and key issues in this area. In this study, the variation points of the precipitation-runoff relationship are defined, the difference between the variation point and the mutation point is distinguished, and the method of variation classification is proposed based on the the dimensionless mean and variation coefficients. Then, a comprehensive diagnosis system of the rainfall-runoff relationship variation is constructed on the basis of systematically summarying and analyzing of the diagnosis method of rainfall - runoff relationship variation at home and abroad. Taking the Weihe River Basin as a case study, the comprehensive diagnosis system is verified by applying it to test the change point the annual runoff time series at the Huaxian hydrological station. And the results show that the comprehensive diagnosis method proposed in this paper is scientific and reasonable.

Keywords: Hydrological elements; Vatiation changes; Comprehensive detecting system; Weihe River basin

Since 1980s, the global climate has changed significantly, and the water cycle of the basin has shown changes varying in degrees. In IPCC 2007, it is clearly pointed out that the potential evapotranspiration in the world basically shows a downward trend, while the actual evapotranspiration is showing an increasing trend[1,2]. Temperature warming plays a decisive role in precipitation and evaporation, while the changes of precipitation and evaporation affect the water cycle in the basin. On the other hand, human activities have become more and more intensive in recent years,

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such as large water conservancy projects construction, urbanization development due to the rapid population growth, and the implementation of soil and water conservation, which have significant impacts on the underlying surface and the water circulation system in the basin[3–6]. Obviously, the significant changes in the water circulation system can lead to the spatiotenporal variation of the rainfall-runoff relationship, and easily cause the occurrence of extreme hydrological events,thus leading to a series of ecological environment problems, and directly threatening the survival and development of human beings[4–6]. Therefore, it is of great significance and has academic value to study the variation of the rainfall-runoff relationship.

Under the changing environment, the hydrological time series has changed significantly, which mainly includes the decreasing runoff and the increasing flood peak. For example, the average annual precipitation in the Weihe Basin has changed little, but the total runoff has decreased by more than 30%, showing a significant decreasing trend[5]. Hydrological time series should be reliable, consistent and representative since it provides the basic information for the planning, design and operation management of water conservancy projects. However, the variation of hydrological time series destroys its the consistency, which directly threatens the safety of water conservancy projects that have been built or are under construction. Hence, it is important to find the variation point accurately.

Aim at this problem, several studies have been investigated in recent years. For example, Karabork[6] and Martinez[7] detected the climatic variation points using Pittitt method. Huo[8] and Zuo[9] analyzed the watershed runoff change points using Mann-Kendall method and Pettitt methods. Xie[10] used Hurst coefficient method to diagnose the runoff variation in several basins sucha as the Chaobai River Basin, the Wuding River Basin, and the Shule River Basin. Li[11] studied the runoff variation in the upper and middle reaches of the Yangtze River by combining the Hurst and Bartels methods. Also, the methods includes copula function[12], Morlet wavelet[13], approximate entropy[14], maximum entropy[15], Heuristic segmentation algorithm[16] and a sliding correlation coefficient[17] have already used in detecting the runoff variation in the Wei River Basin.

On the basis of systematic summary and analysis of the diagnostic methods of hydrological factors variation at home and abroad, the comprehensive diagnosis system and method of rainfall-runoff relationship variation are studied in this study, and the results can help to cope with the influence of changing environment on hydrology and provide scientific basis for water resource planning, design and operation and scheduling.

1. Definition and connotation of variation point

In the mathematics theory, the stagnation, inflection and extreme points have already been defined, which are shown in **Figure 1.** From it, we can see that if the function $f'(x_0)=0$, x_0 is the stagnation point, if the function $f'(x_0)=0$ and $f''(x_0)=0$, x_0 is the inflection point. While if $f(x) \geq f(x_0)$ and $f'(x_0)=0$,x_0 is the extreme minimum point with $f'(x_0)=0$ and fhe extr. If not, x_0 is the extreme maximum point with $f'(x_0)=0$ and $f''(x_0)<0$. Rene Thom (1973) proposed the abrupt theory in 1973, and in which he consisered that the dynamic change of the parameter can be used to described the system, and the system will change to a certain degree, i.e., when the parameter is approach to a critical value[–]. Similarly, in this paper, the hydrological variation point is different from that of mutation point. The mutation point is equivalent to the stagnation point. It is a quantitative change, and the change trend of the sequence is constant. While the variation point is equivalent to the extreme point. It is a qualitative change, and the variation trend of the sequence before and after the change point is changed. That is to say, the variation point is a leap from quantitative change to qualitative change, but the mutation point is the sudden change in quantity.

2. Methods for detecting variation points at home and abroad

Researchers at home and abroad have made many achievements in identifying the hydrological variation points, which can be roughly classified into two categories. One is qualitative detecting method, the other is quantitative detecting method. Qualitative detecting methods mainly include Process line method, Moving average, Hurst coefficient, Kendall rank correlation method, and Accumulated anomaly method, which are simple and easy calculation. It can detect the variation change trend but can not give the exect point. Quantitive methods mainly include Spearman rank correlation method, Jump diagnosis, Sliding T-test, F-test slide, Slide rank sum test, Ordered clustering method, R/S test, Mann-Kendall test method, Bayesian test, the optimal segmentation method process information two-line method. Those methods can quantitatively diagnose the variation point by analyzing the change trends from different theories, indicators and directions. The judgment core, advantages, and disadvantages of above methods are shown in Table 1.

Mehod	**Judgment core**	**Advantages**	**Disadvantages**
Process line method	Random judgment	Simple, easy calculation.	Highly artificial, and it can't apply to test sequences with non- significant trend.
Moving average method	Random judgment	Simple, easy calculation eliminating the influence of sequence fluctuation.	Highly artificial, and it can't apply to test sequences with non- significant trend.
Hurst coefficient method	Random judgment	Simple, easy calculation.	Complex calculation and lack of quantitative judgment.
Accumulative anomaly method	Random judgment	Simple, easy calculation, and it can diagnose the approximate time of variation.	Highly artificial, and lack of quantitative judgment.
Sliding T test	Jump judgment	Simple, easy calculation.	Highly artificial when dividing the sample length.
Cramer Method	Jump judgment	Simple, easy calculation, similar with slide T test	Highly artificial when dividing the sample length.
Yamamoto test	Jump judgment	Test the variation point from the from i climate information and climate noise.	Highly artificial when setting the sample basic line.
Mann-Kendall test	Jump judgment	A non-parametric statistical test method. It does not require to follow a certain distribution, and it is also not interfered by a few abnormal values.	Results depend on the sequence length, different length shows different results.
Pettitt test	Jump judgment	Similar with Mann-Kendall test.	It not widely applied to the climate, hydrology research
Lepage test	Jump judgment	Nonparametric statistical method for testing whether there are significant differences between two independent groups.	It not widely applied to the climate, hydrology research
BG test	Jump judgment	Regarding the variation point detection as a segmentation problem, and finding of the average value of the largest difference among subsequences.	Not available in short sequence
Slide F test	Jump judgment	Unknown mean variance test of two divided samples.	Can not find the exact time of variation point.
Sequential clustering method	Jump judgment	Searching for the optimal segmentation point, minimizing the sum of deviation squares among the same species.	Needing further split sample test

Spearman test	Trend judgment	Trend test by using rank correlation coefficient test	not available in non-significant trend sequence

Table 1. The judgment core, advantages and disadvantages of variation point method

3. Classification

The change degree of of hydrological variation are different, and the corresponding impacts are different. The light change will cause little effects while severe change will cause great imapcts. If there are several variation points detected among one sequence, it is important to find the strongest one, which should pay more attention to. Therefore, to eliminate the limitaions of the above methods, a simple method (function 1, 2), which uses the dimensionless method to deal with the mean value and Cv value of the sequence, is proposed in this study. Using this method, it can get the coefficients of mean and Cv values. Based on the changes of the coefficients, the change degree of the variation point is divided into 7 classifications (Table 2).Here, 0 refers no variation, 1 refers abrupt change, 2 refers light variation, 3 refers medium variation, 4 refers high variation, 5 refers strong variation and 6 refers extreme vatiation.

$$\eta\overline{X} = \frac{\overline{X}_V - \overline{X}_0}{\overline{X}_0} \quad (1)$$

$$\eta\overline{C}_V = \frac{\overline{C}_{V_V} - \overline{C}_{V_0}}{\overline{C}_{V_0}} \quad (2)$$

Where $\eta\overline{X}$ and $\eta\overline{C}_V$ are the coefficients of mean and Cv values, respectively. $\overline{X}_0$ and $\overline{X}_V$ are the mean values of pre-change and post-change, repectively. $\overline{C}_{V_0}$ and $\overline{C}_{V_V}$ are the Cv values of pre-change and post-change, repectively.

Mean coefficient / **Cv coefficient**	**<20%**	**20%~40%**	**40%~80%**	**>80%**
<20%	0	1	2	3
20%~40%	1	2	3	4
40%~80%	2	3	4	5
>80%	3	4	5	6

Table 2. Variation classification distribution

4. Comprehensive detecting system and method for hydrological element variation

4.1 System developing

At present, the methods of testing the abrupt point is not distinguished from the variation point, in which, the mathematical statistics and nonlinear theory is the most commonly used. However, does the abrupt point be the variation point? Do the abrupt points be the results of the limitations of computational methods themselves that lead to? The diagnostic results of variation points may be different with different detecting methods. Although there will be some coincidence phenomenon of variation points, the calculation of the variation points is really the point of variation? All of these issues are worth further studying. Therefore, it is necessary to establish a comprehensive diagnostic variation system to solve the above problems.

The thought of comprehensive diagnostic variation system is learnt from the medical diagnosis which are as follows:

(1). to understand the etiology, pathogenesis and pathology;

(2). to analyze of clinical manifestations;

(3). to construct the index diagnosis system by various examination methods, such as blood biochemical examination, electrocardiogram, echocardiography, radionuclide myocardial imaging, and magnetic resonance imaging.

(4). To obtain the Comprehensive analysis results through analyzing each index and excluding other diseases.

So, we can introduce this idea into the comprehensive diagnostic variation system to diagnose the variation points of hydrological factors. The chart of Comprehensive analysis method is shown in **Figure 2**, which can be mainly divided into 4 steps (**Figure 1**):

(1). Variation background analysis: analyzing the climate change and human activity background, understanding the causes of variation point;

(2). Variation point detecting: determining the possible variation points by using a variety of qualitative and quantitative detecting methods;

(3). Variation classification: classifying the variation point grade based on the mean coefficient and Cv values;

(4). Comprehensive analysis: determining the variation points comprehensively by calculating of the runoff sequence indexes that are before and after the variation points, such as the mean, mean square, Cv, Cs, inter-annual, annual, cycle, trend, sustainability, the rationality analysis.

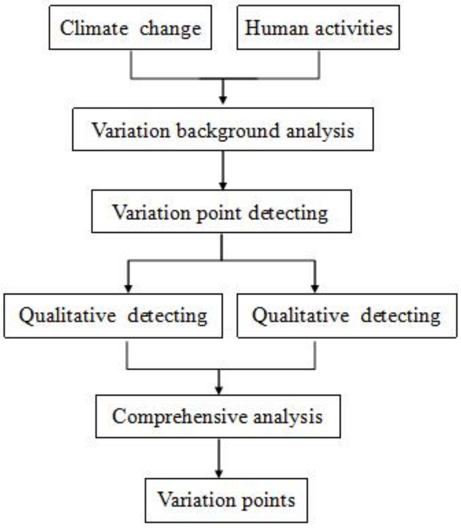


Figure 1. Comprehensive variation detecting system

4.2 Case study

Weihe river, the largest tributary of the Yellow River, originates in Weiyuan County, Gansu Province, and flows through Gansu, Shaanxi and Ningxia provinces, and finally incorporates into the Yellow River in Tongguan, Shaanxi province (**Figure 2**).

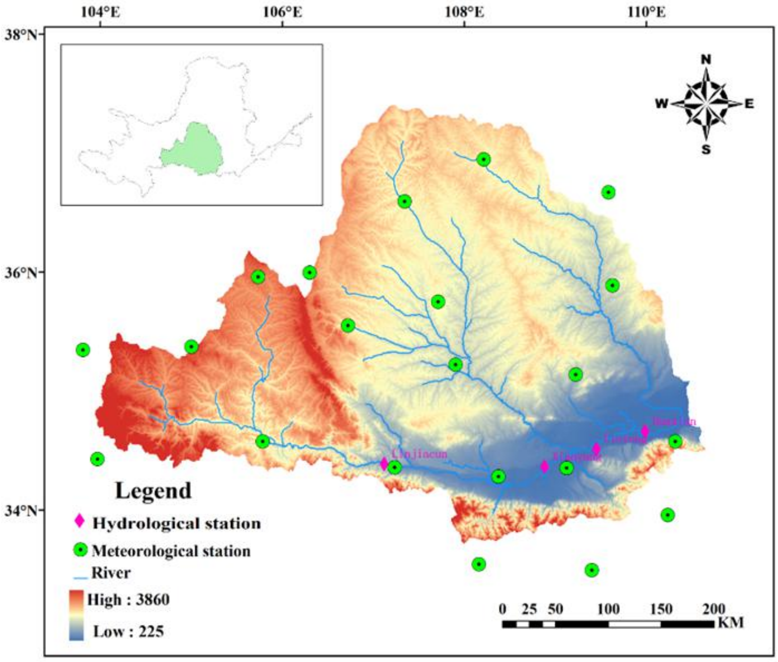


Figure 2. Location the Weihe River basin

Taking the Huaxian station as an example, the relationships between rainfall and runoff are studied to is verify the Comprehensive analysis method by the variation of runoff coefficients with the runoff series from 1960 to 2010, and the rationality of diagnosis results are analyzed.

(1) Variation background analysis:

Analyzing the climate change and human activity background, understanding the causes of variation point. With the global climate change, the climate change in Weihe basin is varied obviously which is shown in figure 3. From figure 3 we can see that all the precipitation, potential evaporation and runoff series are shown different declining trends, in which, the precipitation is decreased by 20mm every 10 years, the potential evaporation is decreased by 7.3mm every 10 years, and the runoff is decreased by 11.6mm every 10 years.

Since 1970, a large-scale of water conservancy constructions have been the implemented in Weihe basin. For example, 1019 reservoirs have been built only in Shaanxi province, with their total capacity being up to 4.973 million m3. There have more than 188 acres irrigated areas, and the effective irrigation areas are up to 997.6 thousand hectares. The total length of levee reaches 6251 km; and 1166 warping dams have been newly constructed and reinforced. The change of hydrological elements is largely impacted by the intensive human activities which can mainly directly or indirectly influence the land use and cover. Therefore, the climate change and human activities provide the conditions for the variation of hydrological factors.

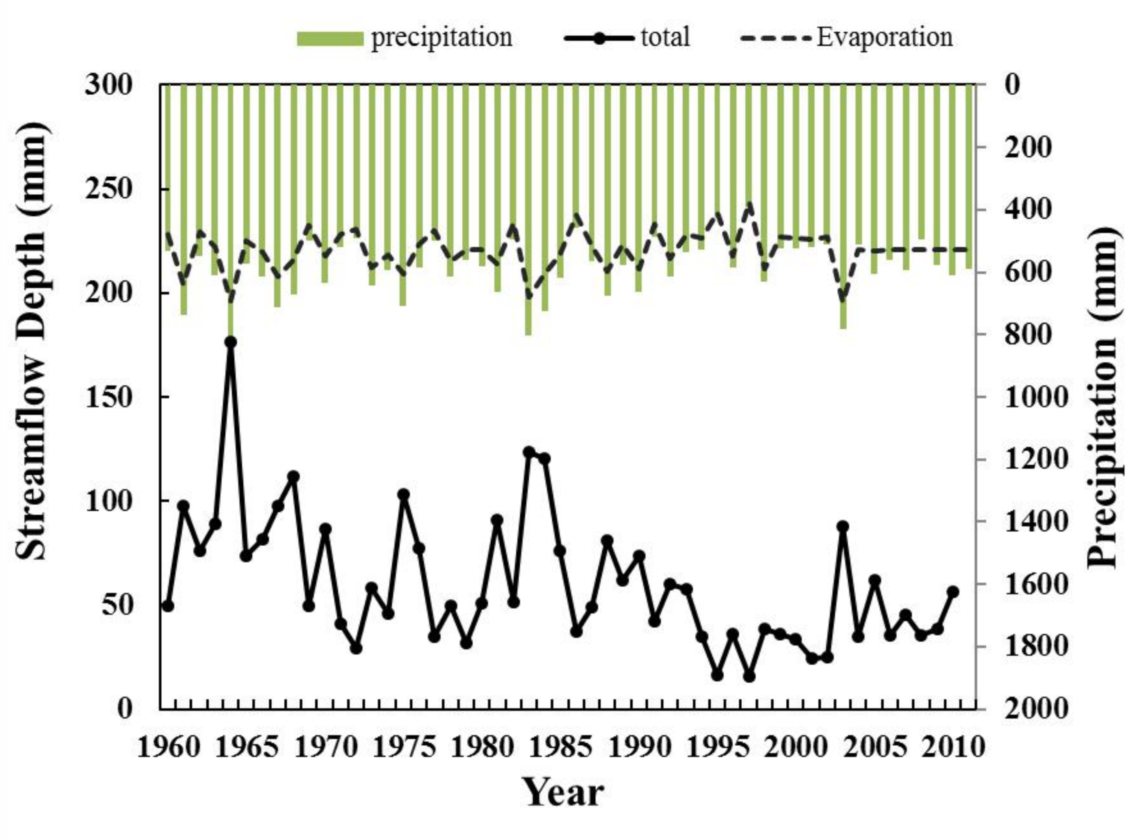


Figure 3. The precipitation, evaporation and streamflow change in Weihe River basin

(2) Variation point detecting:

The variation points at Huaxian station are determined by using a variety of detecting methods, such as the moving average, process line method, Hurst coefficient method. The sliding T, sliding F, ordered clustering method, R/S test and Mann-Kendall test, Cramer (Cramer) test method are all used to quantitatively judge the possible variation points, and there may occur in 1964, 1969, 1980, 1987, 1994, and 2005 (Table 3).

Method	**Possible variation point**		
Slide T test	1964	1980	
Yamamoto method	1969	1981	1994
Mann-Kendall test	1987		
Pettitt test	1994		
Sequential clustering method	1993		
Slide F test	2005		

Table 3. The variation detecting results

(3) Variation classification:

The variation point grade is classified based on the mean coefficient and Cv values which is shown in figure 4. Taking the variation point as the dividing point, the sequence is divided into two parts. From the figure 4, we can see that the possible variation points are occurred in 1964, 1969, 1994, 1987, 2005, in which, the years of 1987 and 1994 are light variation, and the years of 1964 and 1969 are medium variation, and the year of 2005 is high variation.

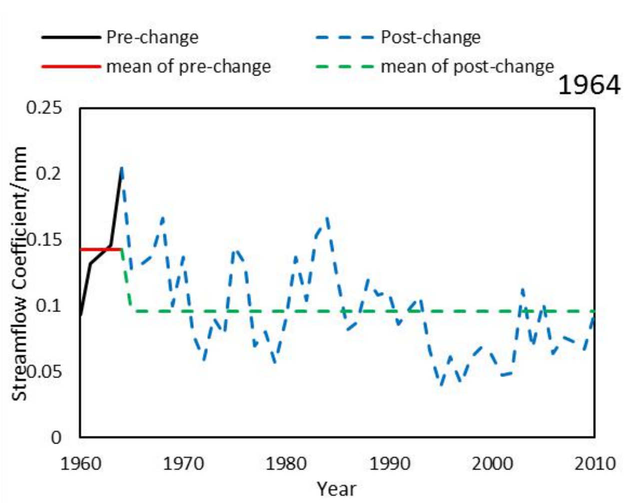
Possible variation point	$\eta\overline{X}$	$\eta\overline{C}_V$	**Degree**	**Level**

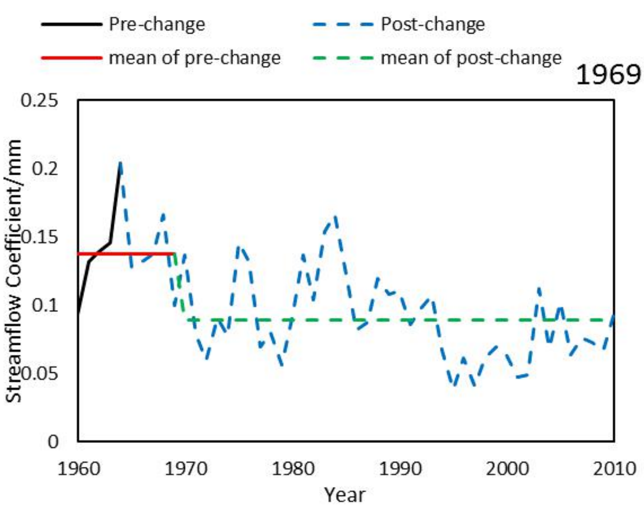
1964	48.69%	-27.69%	3	Medium variation
1969	54.28%	-35.25%	3	Medium variation
1980	29.78%	-6.60%	1	Abrupt
1987	48.91%	2.43%	2	Light variation
1994	66.19%	3.18%	2	Light variation
2005	28.01%	93.34%	4	High variation

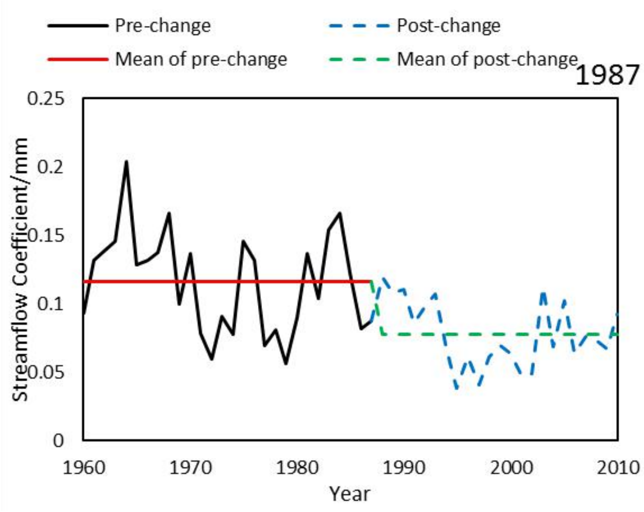
Table 4. Variation classification results

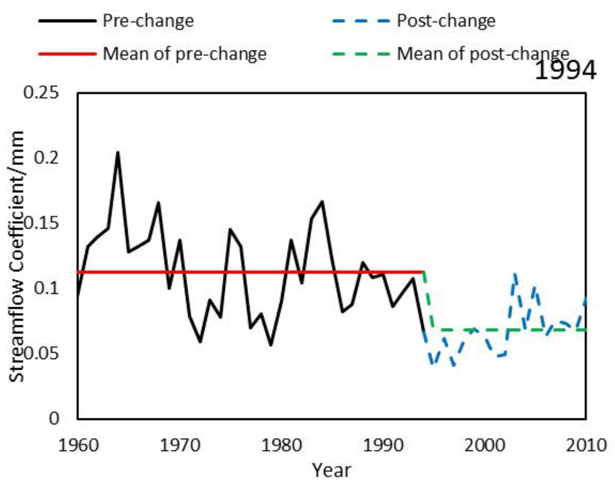
(4) Comprehensive test

Based on the step (3), the years of 1964, 1969, 1987, 1994 and 2005 are determined as the possible variation points. Taking these variation points as the dividing points, the sequence is divided into two parts. Then the basic characteristics of net coefficient for two parts, such as trend and sustainability, are all analyzed. Finally, the variation points can be comprehensively determined. the change results of mean values, maximum, cycles and trends are shown in in Table 4, Table 5, Table 6, and Table 7, respectively. From these tables, we can see that the variation points are changed obviously. There have similar change characteristics before and after 1964 and 1969. the years of 1964 and 1990 are slightly varied, and the year of 1994 is moderately varied, and the year of 2005 is strongly varied. Since the years of 2005 and 1964 are close to the starting year (1960) and the ending year (2010) of the sequence, respectively, these two points does not been considered in this paper. Therefore, the years of 1969、1987 and 1994 are finally diagnosed as the variation points at Huaxian station in the Weihe river, and the year of 1994 are moderately varied, which should be paid highly attention to.









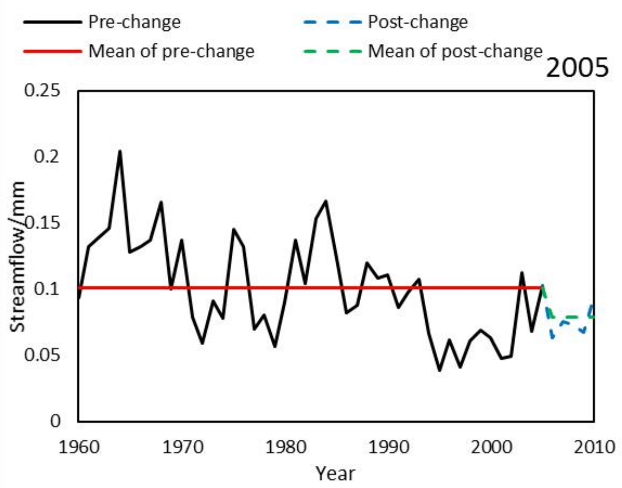


Figure 4. The mean value change in pre-change and post-change

Variation point	Period	Maximum	Mean
1964	1960-1964	0.20	0.14
	1965-2010	0.17	0.09
1969	1960-1969	0.20	0.14
	1970-2010	0.17	0.09
1987	1960-1987	0.20	0.12
	1988-1990	0.12	0.08
1994	1960-1994	0.20	0.11
	1995-2010	0.11	0.07
2005	1960-2005	0.20	0.10
	2005-2010	0.10	0.08

Table 5. The maximum change in pre-change and post-change

Variation point	Pre-change period	Post-change period
1964	3,5	6,15
1969	4,7,13	3,7,10
1987	3,6,16	3,7,10
1994	5,18	4,13
2005	5,17	
1960-2010	6,17	

Table 6. The periodicity change in pre-change and post-change

Variation point	Period	Kendall	Trend	Hurst	Persistent
1964	1960-1964	2.45	Significant increase	0.65	positive
	1965-2010	-3.21	Significant decline	0.77	positive
1969	1960-1969	1.34	Non-signiticant increase	0.85	positive
	1970-2010	-2.18	Significant decline	0.8	positive
1987	1960-1987	-1.22	Non-significant decline	0.88	positive
	1988-1990	-0.92	Non-significant decline	0.64	positive
1994	1960-1994	-1.95	Significant decline	0.83	positive
	1995-2010	2.61	Significant increase	0.86	positive
2005	1960-2005	-3.76	Significant decline	0.81	positive
	2005-2010	0.98	Non-signiticant increase	0.71	positive

Table 7. The trend and persistent change in pre-change and post-change

5. Conclusions

On the basis of systematically analyzing the variation points diagnosis methods of hydrological factors at home and abroad, this paper proposed a Comprehensive variation detecting syste. in order to test the variation changes, it choosed the Huaxian station at Weihe River basin as a test case to detect the precipitation – runoff relathionship variation. The mainly conclusions are as follows:

The variation points are defined and distinguished from the abrupt point, and its connotation is described. The variation classification grade of hydrological factors is proposed. Based on the value analysis and coefficient variation degree of sequence, the hydrological variation is divided into 7 grades by using the dimensionless of the sequence mean and Cv values and excluding the limitations of various methods themselves. Based on a comparative analysis of the characteristics and advantages/ disadvantages of various detecting methods, a Comprehensive analysis method of hydrological factors variation is proposed by using the thoughts of the definition of stagnation, inflection point and extreme point in mathematical and the diagnosis method in medicine. Four steps of the Comprehensive analysis method are given as 1) Variation background analysis: analyzing the climate change and human activity background, understanding the causes of variation point; 2) Variation point detecting: determining the possible variation points by using a variety of qualitative and quantitative detecting methods; 3) Variation classification: classifying the variation point grade based on the mean coefficient and Cv values; 4) Comprehensive analysis: determining the variation points comprehensively by calculating of the runoff sequence indexes that are before and after the variation points, such as the mean, mean square, Cv, Cs, inter-annual, annual, cycle, trend, sustainability, the rationality analysis.

Taking the Huaxian station in the Weihe basin as an example, the method proposed in this paper is verified, and the years of 1969, 1987 and 1994 are finally dertermined as the variation points through the Comprehensive analysis of annual runoff series from 1960-2010.

In summary,the comprehensive Variation point detecting method of hydrological elements is studied in this paper. Then the relationship between rainfall and runoff Huaxian station in the Weihe River Basin is diagnosed. Finally, the the variation points and their grades are obtained. The year of 1994 are moderately varied. It should be paid highly attention to in hydrological analysis and calculation, and it should be also considered in the planning, design and operation of water resources to better deal with the impacts of changing environment.

Acknowledgments

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